Hazard screening and UK risk prioritisation for tyre additives

Chief Scientist's Group report

July 2025

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Dr Robert Bradburne
Chief Scientist

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Executive Summary

Tyres are made from a complex mix of synthetic and natural rubbers, along with hundreds of chemical additives. Emissions of rubber in tyre wear particles (TWP), and subsequent leaching of substances contained within them may pose potential risks to the environment. The Environment Agency (EA) has previously undertaken work to assess the emissions and fate of TWP and its leaching potential to establish an exposure scenario for rubber additives in the UK environment. Due to the large number of chemicals used as additives in the manufacture of tyres there is a need to prioritise which substances should be considered for further detailed assessment. This project had the objective of prioritising tyre additives based on both their environmental hazard and potential risk. The physical effects of microplastic pollution have not been considered.

61 substances (including a small number of transformation products) were selected for hazard-based prioritisation based on consideration of previous assessments performed by regulators and scientific researchers. Substances were prioritised using a quantitative scoring system based on hazard criteria and exposure based on market volume and use in tyres. Qualitative categories were then assigned based on the scores: ‘Of concern’ (14 substances), ‘Of potential concern’ (29 substances), ‘Lower concern’ (14 substances) and ‘Could not be assessed’ (4 substances without sufficient data for assessment).

Based on the prioritisation process, 18 substances were taken forward for further risk-based assessment. These included all of the ‘Of concern’ substances and some of the highest scoring substances from the ‘Of potential concern’ category. In addition, two transformation products were taken forward based on specific concerns about their toxicity in the scientific literature. Exposure and risk assessments were performed using the EA’s draft TWP exposure scenario and EUSES model; tyre additives were ranked according to the highest predicted risk characterisation ratio for environmental compartments such as water, sediment and soil. The modelling was undertaken for prioritisation purposes and does not mean that chemicals in tyres are causing an actual environmental risk in Great Britain that is not adequately controlled.

Strikingly different results were generated by the hazard and risk-based prioritisations. The hazard-based assessment generally gave the highest ranking to substances well known as environmental pollutants, e.g. octylphenol, zinc oxide and benzotriazole. In contrast, these substances came near the bottom of the risk-based prioritisation that gave the highest rankings to the vulcanising agents DCBS and MBTS, and the phenylenediamine derivative (PPD) antiozonants and their degradation products. This difference in the hazard prioritisation rankings is likely due to more information being available for the well-known and better characterised environmental pollutants compared to the lesser-known substances primarily used

as tyre additives, which affects the size of the assessment factors used for deriving predicted no effect concentrations (PNECs). Also, the hazard-based assessment flagged which substances have been classified for toxicity to the aquatic environment, but did not discriminate further according to the degree of toxicity.

Recommendations are made for a more detailed review of the highest priority substances, particularly PPDs. Furthermore, monitoring could be undertaken for the substances ranked highest by the risk-based prioritisation, with a focus on the environmental compartments identified as most sensitive for each substance.

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1 Introduction

Tyres are made from a complex mix of synthetic and natural rubbers, along with hundreds of chemical additives. Tyres undergo wear when in contact with the road surface, and they have been identified as the source of a significant proportion of microplastics in the environment (HE, 2020). In addition to rubber, there are many other substances present in tyre debris, such as fillers, stabilizers, cross-linking agents and secondary components (e.g. pigments, oils and resins). Specific types of chemicals of potential concern include heavy metals (e.g. zinc), benzothiazoles, phthalates and phenolics (e.g. alkylphenols), which may be toxic or affect the endocrine system. Emissions of rubber in tyre wear particles (TWP), and subsequent leaching of substances contained within them, are therefore considered to pose potential risks to the environment.

Some tyre additives have been identified as being toxic to aquatic organisms. For example, a link has been identified between the commonly used tyre additive 6PPD (N-1,3-dimethylbutyl-N′-phenyl-p-phenylenediamine) and mortality events involving Coho Salmon (*Oncorhynchus kisutch*) that are thought to be primarily due to toxicity of the breakdown product 6PPD-quinone (6PPD-Q, Tian *et al.* (2021)). As tyres are both manufactured and imported in the UK, this substance is a potential risk to aquatic organisms exposed to runoff from our roads. 6PPD is just one example of a range of PPD antidegradants used in tyres, some of which might give rise to common transformation products that may be more hazardous than the parent compounds.

Due to the large number of chemicals used as additives in the manufacture of tyres prioritisation is needed to identify candidates for further assessment, based on their environmental hazard and potential risk. To this end, a recent project commissioned by the EA gathered information on the emissions and fate of tyre wear particles and their leaching potential to establish an exposure scenario for rubber additives in the UK environment (EA, Unpublished). This included a model to predict the mass of TWP (in the form of tyre rubber) released and the subsequent leaching of additives and degradants (i.e. the transformation products formed due to use of tyres and subsequent weathering of TWP in the environment). It also identified several substances for potential further prioritisation based on hazard screening data. This report was commissioned to develop the prioritisation process further. The physical effects of microplastic pollution have not been considered.

The report covers five main areas:

- Preparation of an initial list of relevant substances based on the 47 substances identified from the EA (Unpublished) report and supplemented with additional substances taken from relevant publications (Section 2).
- Compilation of environmental fate, hazard data, PNECs and use data compiled from regulatory reports and EU REACH dossiers, supplemented by on-line

databases and the scientific literature. This information was used to undertake a preliminary hazard screen, based on existing environmental hazard classifications and criteria for persistence, bioaccumulation and toxicity (PBT) (including very persistent, very bioaccumulative, vPvB); persistence, mobility and toxicity (PMT) (including very persistent, very mobile, vPvM); and endocrine disruption (ED) potential (Section 3).

- A hazard-based prioritisation in conjunction with UK and EU REACH registration data, including tonnage and regulatory concerns. Relevance to the UK and current regulatory activity is used to guide the prioritisation. Substances are grouped into either ‘Of concern’, ‘Potential concern’ or ‘Lower concern’ categories (Section 4).
- Risk-based prioritisation based on exposure assessment to generate Predicted Environmental Concentrations (PECs) for the UK environment using the EA’s model for tyre particle leaching and the EUSES model. PECs are compared to PNECs to estimate risk characterisation ratios (RCRs) that indicate the level of risk posed (Section 5).
- Conclusions and recommendations (Section 6).

2 Development of the substance list

The first objective of this project was to develop an initial list of tyre additive substances. This was compiled from regulatory reports provided by the EA and a literature search was undertaken to identify recent papers, and specifically review papers, which identified the constituents of tyres and tyre-derived materials such as crumb fill. The regulatory reports provided by the EA are listed below:

- EA (Unpublished) - Environmental Exposure Scenarios for Particles and Chemicals Released from Tyres (specifically, Annex 5: Substances used in the manufacture of rubber and Annex 6: Candidate substances for addition to monitoring requirements).
- OECD (2004) - Emission Scenario Document on Additives in Rubber Industry.
- DEFRA (2019) - Investigating the sources and pathways of synthetic fibre and vehicle tyre wear contamination into the marine environment.
- National Highways (2023a, 2023b, 2023c) - Microplastics and contaminants of concern in the strategic road network - SPATS Framework Reports.
- ECHA (2021) - Annex XV Investigation Report - Risk Assessment of Fill Material.

A number of tyre additives have been reviewed under the EA's Prioritisation and Early Warning System (PEWS, described in Sims (2022)) and these assessments were provided by the EA. The EA also provided information on tyre additives that had been obtained from the British Tyre Manufacturers Association (BTMA).

The key papers identified from the literature search and used to populate the initial list of tyre additive substances are listed below:

- Brandsma *et al.* (2019)
- Gomes *et al.* (2021)
- Johannessen *et al.* (2022)
- Boisseaux *et al.* (2024)
- Mayer *et al.* (2024)

As chemicals in tyres have been receiving attention by regulators and academics in recent years, given the resource available and in the interests of efficiency, the initial list was screened to identify those substances that have already been subject to some form of review. The following criteria were used to select the substances (in order of weighting):

- Substance features in a regulatory report and a minimum of two review papers, or two regulatory reports, including one external regulatory report (i.e. from an authority other than the EA).

- Substance features in an EA report or assessment (EA (Unpublished) Annexes 5 & 6 or PEWS), and two review papers.
- Substance features in an external regulatory report and one review paper.
- Substance features in a regulatory report or review paper and has specific sector interest (e.g. flagged by Highways England, National Highways (NH), BTMA or PEWS listing).
- Substance has been identified as a potential substitute for a hazardous substance.

The selected substances, grouped by their technical function, and concentration in tyres or tyre-derived material, where available, are listed in Table 2.1; the source documents are detailed in Annex 1. Some chemicals, such as 4-tert-octylphenol (t-OP), may be present as impurities in intentionally added chemicals. No adjustments (i.e. concentration or presence) were made to account for where in the tyre a chemical is used - some chemicals are used in tyre sidewalls which do not typically generate TWP.

There are concerns that some transformation products of tyre additives may be more toxic that their parent compounds (e.g. Tian *et al.* (2021)) so several of these were also included in the assessment:

- N,N'-diphenylurea (DPU, CAS no. 102-07-8) – degradation product of diphenylguanidine and previously assessed in PEWS.
- Diphenylamine (DPA, CAS 122-39-4), degradation product of diphenylamine derivatives such as ADPA.
- 6PPD-quinone (6PPD-Q, CAS 2754428-18-5), degradation product of 6PPD (Tian *et al.*, 2021).
- IPPD-quinone (IPPD-Q, CAS 68054-73-9) degradation product of IPPD.

Table 2.1: Selected tyre additives and measured concentration in tyres and tyre-derived material

Chemical name	Abbreviation	CAS number	Maximum measured concentration (mg/kg)	Reference for maximum concentration
PHTHALATE PLASTICISERS				
Di-n-butylphthalate	DBP	84-74-2	14	ECHA (2021)
Di(2-ethylhexyl) phthalate	DEHP	117-81-7	59	Mayer *et al.* (2024)
Diethyl phthalate	DEP	84-66-2	2.5	Gomes *et al.* (2021)
Diisobutyl phthalate	DiBP	84-69-5	29	Mayer *et al.* (2024)
Benzyl butyl phthalate	BBP	85-68-7	2.8	Gomes *et al.* (2021)
Dioctyl phthalate	DOP	117-84-0	1.0	ECHA (2021)
BENZOTHIAZOLE VULCANISING AGENTS				
Benzothiazole	BTZ or BZT	95-16-9	30.99	ECHA (2021)
Benzothiazole-2-sulfonic acid	BTSA	941-57-1	-	
Hydroxybenzo-thiazole	HOBT	934-34-9	33.63	Gomes *et al.* (2021)
2-Mercapto-benzothiazole	MBT	149-30-4	205	Mayer *et al.* (2024)
2-Methylbenzo-thiazole	MeBT	120-75-2	-	
N-Cyclohexyl-benzothiazol-2-sulfenamide	CBS	95-33-0	-	
2-(4-Morpholinyl)-benzothiazole	24MoBT	4225-26-7		
N-Cyclohexyl-2-benzothiazol-amine	NCBA	28291-75-0	3.9	Gomes *et al.* (2021)
2-Benzothiazole-sulfenamide		2801-21-0	-	
Di(11-benzothiazole-2-yl) disulfide	MBTS	120-78-5	2.1	Mayer *et al.* (2024)
2-Methylthio-benzothiazole	MeSBT	615-22-5	<3	Mayer *et al.* (2024)
VULCANISATION ACCELERATORS				
Diphenyl guanidine	DPG	102-06-7	650	Mayer *et al.* (2024)

Chemical name	Abbreviation	CAS number	Maximum measured concentration (mg/kg)	Reference for maximum concentration
N,N-Dicyclohexyl-benzothiazole-2-sulfenamide	DCBS	4979-32-2	-	
N-tert-Butylbenzo-thiazole-2-sulfenamide	TBBS	95-31-8	-	
Tetramethyl thiuram disulfide	TMTD	137-26-8	-	
CYCLIC AMINE ANTIOXIDANTS				
Cyclohexyl-3-phenylurea	CPU	886-59-9	-	
Cyclohexylamine	CHA	108-91-8	69	Mayer *et al.* (2024)
Aniline		62-53-3	11	Mayer *et al.* (2024)
Dicyclohexyl-amine	DCHA	101-83-7	-	
1,3-Dicyclohexyl-urea	DHU or DCU	2387-23-7	-	
N-Methyl-dicyclo-hexylamine	mDCHA	7560-83-0	-	
ALKYL PHENOL ANTIOXIDANTS				
Isononylphenol		11066-49-2	21.6	Gomes *et al.* (2021)
4-tert-Octylphenol	t-OP	140-66-9	27.8	Gomes *et al.* (2021)
2,2′-Methylene-bis(4-ethyl-6-*tert*-butylphenol)	o-MBp24	88-24-4	-	
PHENYLENEDIAMINE ANTIOZONANTS				
N-(1.3-Dimethyl-butyl)-N′-phenyl-p-phenylene-diamine	6PPD	793-24-8	1200	Mayer *et al.* (2024)
N-Isopropyl-N′-phenyl-1,4-phenylene-diamine	IPPD	101-72-4	-	
N-Phenyl-N′-cyclohexyl-p-	CPPD	101-87-1	-	

Chemical name	Abbreviation	CAS number	Maximum measured concentration (mg/kg)	Reference for maximum concentration
phenylene-diamine				
N,N′-Diphenyl-p-phenylene-diamine	DPPD	74-31-7	-	
N,N′-Di(ortho-tolyl)-p-phenylene-diamine	DTPD	27417-40-9	-	
N,N’-Bis(1,4-Dimethyl-pentyl)-p -phenylenediamine	77PD	3081-14-9	-	
N,N′-Di-2-naphthyl-p-phenylene-diamine	DNPD	93-46-9	-	
N-(1,4-Dimethyl-pentyl)-N’-phenylbenzene-1,4-diamine	7PPD	3081-01-4	-	
1,4-Benzene-diamine, N,N'-mixed Ph and tolyl derivs.	BENPAT	68953-84-4	-	
N-(1-Methyl-heptyl)-N′-phenyl-p-phenylene-diamine	8PPD	15233-47-3	-	
N,N'-Di-sec-butyl-p-phenylene-diamine	44PD	101-96-2	-	
4-(1-Methyl-1-phenylethyl)-N-[4-(1-methyl-1-phenylethyl) phenyl]aniline		10081-67-1	-	
OTHER ANTIDEGRADANTS				
Acetone diphenylamine condensate	ADPA	68412-48-6	-	
2,2,4-Trimethyl-1,2-Dihydro-quinoline polymer	TMQ	26780-96-1	-	

Chemical name	Abbreviation	CAS number	Maximum measured concentration (mg/kg)	Reference for maximum concentration
1H-Benzotriazole	BTA	95-14-7	-	
5-Methyl-1H-benzotriazole	5-MTBR	136-85-6	-	
2-(2H-Benzotriazol-2-yl)-6-(1-methyl-1-phenylethyl)-4-(1,1,3,3-tetra-methylbutyl)-phenol	UV-928	73936-91-1	-	
OTHER TYRE ADDITIVES				
Zinc oxide	ZnO	1314-13-2	10,464	ECHA (2021)
Triphenyl phosphate	TPP	115-86-6	-	
Ethoxyquin		91-53-2	-	
Methyl isobutyl ketone	MIBK	108-10-1	3.34	
Stearic acid		57-11-4	-	
Indanone		83-33-0	5.26	Mayer *et al.* (2024)
6,6'-Di-tert-butyl-2,2'-methylenedi-p-cresol	DBMC	119-47-1		
Tris(4-nonylphenyl, branched and linear) phosphite (TNPP) with ≥ 0.1% w/w of 4-nonylphenol, branched and linear (4-NP)			-	
Hexa(methoxy-methyl)melamine	HMMM	3089-11-0	-	
DEGRADATION PRODUCTS				
Diphenylamine	DPA	122-39-4	-	
Phenylguanidine	PG	2002-16-6	-	
Diphenyl urea	DPU	102-07-8	-	
6PPD-quinone	6PPD-Q	2754428-18-5	-	
IPPD-quinone	IPPD-Q	68054-73-9	-	

3 Data compilation and hazard assessment

Based on the substance list developed in the previous task, a primarily hazard-based prioritisation process was developed to objectively identify those substances of highest concern. The prioritisation was based on both hazard (toxicity (assessed based on hazard classification under the Classification, Labelling and Packaging (CLP) Regulation), persistence, bioaccumulation, mobility and ED) and exposure (assessed based on registered tonnage in the UK and EU and percentage in tyres, as proxies for increased likelihood of exposure). The relevant data to support this assessment were collated and additional data on physico-chemical properties (e.g. water solubility, vapour pressure, etc.) and PNECs were also collated as part of this task. Although the PNECs and physico-chemical data were not directly used for the prioritisation exercise, they were collated at this point as they are used as inputs in the modelling and risk assessment conducted in later tasks (Section 5).

The full list of collated endpoints is as follows:

- Substance identity information (chemical name, IUPAC name, synonyms, CAS number, EC number, SMILES code, molecular weight, chemical structure and the broad chemical group to which the substance belongs (e.g. benzothiazoles)). Where available, information on transformation products was also included.
- Use information (tonnages produced in both the UK and EU, an indication of whether the reported uses are likely to be relevant to tyres and the technical function of the substance in tyres).
- Physico-chemical and environmental fate properties (water solubility, n-octanol–water partition coefficient (log K_{OW}), vapour pressure, Henry's Law constant, biodegradation (indication of ready biodegradation and degradation rates, where available), adsorption (soil organic carbon–water partition coefficient, log K_{OC}) and bioaccumulation (aquatic bioconcentration factor, BCF and n-octanol–air partition coefficient (K_{OA})).
- Hazard information (classification under UK and EU CLP, any hazard flags highlighted by ECHA (e.g. PBT/vPvB, PMT/vPvM or ED), an indication of whether the substance is a priority substance or specific pollutant listed under the EU Water Framework Directive (WFD, EC (2000)), PNEC values, key aquatic, sediment and terrestrial toxicity data and results from the US EPA ToxCast database (US EPA, 2025c, accessed August 2024) as an indication of ED potential).

The primary data source was the ECHA portal (ECHA, 2023b, accessed 4th August 2024) which contains information submitted as part of EU REACH registrations. UK REACH registration information was used to provide an indication of the amount of substance manufactured or imported into Great Britain. Downstream user import notifications (DUINs) were also checked. Summary datasets compiled for some substances by the EA as part of the PEWS screen were also used as data sources, where available. For substances where data gaps remained after consulting these sources, the US EPA CompTox dashboard (US EPA, 2025b, accessed August 2024) was used to identify relevant physico-chemical and environmental fate data. Where the values cited on this platform were based on quantitative structure activity relationship (QSAR) predictions, these were included along with a reference to the QSAR model used and an indication as to whether the substance was inside or outside the model domain for this prediction (based on the information provided on the CompTox dashboard). Additional data sources used for gap filling, where necessary, included PubChem (NIH, 2023, accessed August 2024) and the US EPA Ecotox database (US EPA, 2025a, accessed August 2024). Sources were searched in a tiered manner; where information for all data points was obtained from an earlier source (e.g. REACH registration dossier), sources further down the hierarchy (e.g. PubChem) were not searched. For substances where PNEC values were not available in the REACH registration dossiers, the NORMAN Ecotoxicology database – Lowest PNECs (NORMAN Network, 2025, accessed September 2024) was searched, although it is noted that there are potential limitations with the reliability of values taken from this source, particularly when based on modelled data. For those substances with limited or no data available from the sources listed above, QSAR predictions were carried out using the US EPA EPISuite (v 4.1) models (US EPA, 2024), with an indication of the potential reliability of the predictions also compiled into the prioritisation database.

The data collated are considered to come from broadly reliable sources, but it is acknowledged that the data included in REACH registration dossiers have not always undergone regulatory review and therefore there may be errors or discrepancies in these data, which could carry through when the data are used as the basis for hazard assessment (e.g. PBT assessment). Detailed assessment of the reliability of all of the data was beyond the scope of this project. However, additional regulatory sources were also searched to identify any hazard flags raised by regulators for the selected substances. ECHA's PACT tool (ECHA, 2023a, accessed September 2024) was searched, which provides an indication as to whether a substance has been flagged as a (potential) substance of very high concern (SVHC), is subject to authorisation or restriction under EU REACH, is proposed for harmonised classification or has been, or is undergoing, assessment for PBT, PMT or ED concerns. UK mandatory classifications were checked by reviewing the Mandatory Classification and Labelling (MCL) list (HSE, 2021, accessed September 2024). The WFD list of Priority Substances and Specific Pollutants was also reviewed to identify substances that have been flagged under the WFD. Where substances have been proposed, but not confirmed, as Priority Substances or for inclusion on the WFD Watch List this is also indicated. Data sources were searched in August and September 2024 and information was collated in a prioritisation database.

Based on the collated data, PBT/vPvB and PMT/vPvM potential was assessed by comparison with the EU REACH criteria (ECHA, 2017; Table 3.1; European Parliament and Council, 2024).

Table 3.1 PBT/vPvB and PMT/vPvM criteria

Criteria	PBT/PMT	vPvB/vPvM
Compartment / degradation half-life	**Persistent**	**Very Persistent**
Marine water	>60 days	>60 days
Freshwater	>40 days	>60 days
Marine sediment	>180 days	>180 days
Freshwater sediment	>120 days	>180 days
Soil	>120 days	>180 days
Bioconcentration factor (BCF)	**Bioaccumulative**	**Very Bioaccumulative**
BCF in aquatic species	>2000	>5000
Adsorption/desorption	**Mobile**	**Very Mobile**
Lowest Log Koc at pH 4-9	<3	<2
Criteria	**Toxic**	**-**
Long-term NOEC/EC10 for marine or freshwater	<0.01 mg/L	-
Classification	Carcinogenic (1A or 1B), mutagenic (1A or 1B), reprotoxic (1A, 1B or 2) (CMR)	-
Evidence of chronic mammalian toxicity	Specific target organ toxicity after repeated exposure (STOT RE 1 or 2)	-

For the purposes of this exercise, substances considered to meet the criteria in Table 3.1 were determined to be PBT/vPvB or PMT/vPvM and substances definitively not meeting the criteria were considered not PBT/vPvB or PMT/vPvM. However, for some substances a concern remains but there are insufficient data to fully conclude (e.g. not readily biodegradable but no higher tier degradation data available); these substances are considered as potentially PBT/vPvB or potentially PMT/vPvM.

The above PMT/vPvM criteria only apply in the EU, and this is not a formal hazard class in the UK. Nevertheless, the information has been included for completeness.

In addition, bioaccumulation was also assessed for air-breathing terrestrial organisms, based on a combination of the K_{OA} and K_{OW}. The thresholds from Arnot *et al.* (2022) were used, with substances with a log K_{OA} <6 assigned 'low' concern, substances with a log K_{OA} of >6 being assigned 'medium' concern and substances with a log K_{OA} >8.5 assigned 'high' concern. The corresponding thresholds for log K_{OW} were log K_{OW} <2 for 'low' concern, log K_{OW} >2 for 'medium' concern and log K_{OW}

>3 for ‘high’ concern. Substances with ‘high’ concern for both log K_{OW} and log K_{OA} were then considered to be of concern for air-breathing organisms (strong threshold) and substances with ‘medium’ concern were considered to be of potential concern for air-breathing organisms.

For ED, a full ED assessment is out of scope of this project. Instead, ED concern was flagged based on substances where a regulatory concern for ED has been highlighted, and substances with ED flags based on information taken from the US EPA ToxCast database.

4 Hazard Screening Prioritisation

A quantitative prioritisation process was then carried out based on the data compiled in the previous task. This was developed to identify the substances of most concern based on hazard and/or exposure in an unbiased manner and to provide a process that could be followed for future prioritisations, if required. Prior to the quantitative scoring, an initial screen was conducted based on environmental hazard classification and regulatory hazard flags. Substances that had no environmental hazard classification, and for which no environmental concerns were identified based on the regulatory data sources searched, were screened out at this stage and categorised as ‘Lower concern’.

The scoring scheme used for the quantitative prioritisation is outlined in Tables 4.1 and 4.2.

Table 4.1 Scoring approach for hazard criteria

Criteria	Threshold	Points
Environmental hazard	No PBT/vPvB or PMT/vPvM concern and no environmental classification	0
	H412, H413 classifications based on EU harmonised classification, self-classification or CLP notification	1
	Potentially PBT or vPvB, potentially PMT or vPvM, or H400, H410, H411 classifications based on EU CLP notifications	3
	Concluded PBT or vPvB, concluded PMT or vPvM, or H400, H410, H411 classifications based on MCL, EU harmonised classification or self-classification	4
Endocrine disruption	No flags for ED concern	0
	Potential ED concern for the environment	1
	Concluded as ED for the environment	2

Hazard statement descriptions can be found within the Guidance on Labelling an Packaging in Accordance with Regulation (EC) No. 1272/2008 (ECHA, 2024). PBT was assessed based on aquatic bioaccumulation as well as bioaccumulation for air-breathing organisms. The criteria for air-breathing organisms were: No PBT/vPvB concern with B based on air-breathing organisms [**0 points**]; PBT/vPvB with B based on air-breathing organisms [**1 point**]; PBT/vPvB with B based on air-breathing organisms - strong threshold (see Section 3 for determination of ‘strong’ threshold) [**2 points**]. However, points were only assigned for substances which scored 0 based on PBT assessment using aquatic bioaccumulation criteria. Including the PBT criteria based on air-breathing organisms was found not to affect the overall scoring for the substances included within the prioritisation.

Differentiation was made between the source of classification information due to differences in the likely reliability of the classification information: EU harmonised classifications have undergone regulatory approval and are considered reliable (unless replaced by a different MCL); self-classifications in REACH registration dossiers have been agreed by all registrants and therefore also have a degree of reliability; CLP notifications have lower reliability because any supplier can make a notification (often leading to divergences), and the data used are not reported.

Table 4.2 Scoring approach for exposure criteria

Criteria	Threshold	Points
Manufacture or import tonnages	≥1 but <10 tonnes (EU tonnage)	0
	≥10 but <100 tonnes (EU tonnage) OR ≥1 but <10 tonnes (UK tonnage)	1
	≥100 but <10,000 tonnes (EU tonnage) OR ≥10 but <100 tonnes (UK tonnage)	2
	≥10,000 but <1,000,000 tonnes (EU tonnage) OR ≥100 but <10,000 (UK tonnage)	3
	≥1,000,000 tonnes (EU tonnage) OR ≥10,000 but <1,000,000 tonnes (UK tonnage)	4
Percentage of the substance in tyres	Included in tyres at <2%	1
	Included in tyres ≥2 - <10%	2
	≥10%	3

The concentration of chemicals within tyres is largely proprietary data and so not publicly available. Where the concentration within a tyre was not known for a specific substance, the concentration of the chemical function group was used (i.e. antiozonants are estimated to make up 2% of a tyre by mass, so 6PPD would be assumed to be present at a 2% concentration). The concentration and presence of a given substances is likely to vary between tyre types and brands, and so while measured data provide an indication of possible concentrations, further dialogue with industry would be needed to understand how representative these are.

The scores for each criterion were added together (without further weighting) and used to rank the substances. Qualitative hazard categories were then assigned to the substances based on these quantitative scores.

- Substances scored between 7 and 10 were assigned to the category ‘Of concern’
- Substances scored between 1 and 6 were assigned to the category ‘Of potential concern’
- Substances scored 0 were assigned to the category of ‘Lower concern’
- Substances with very limited or no data were assigned to the category ‘Cannot be assessed’

This approach led to 14 substances being assigned ‘Of concern’ and 29 substances ‘Of potential concern’. For the next stage of the project, it was decided to assess all of the substances in the ‘Of concern’ category. For the substances ‘Of potential concern’, expert judgement was used to refine the number of substances taken forward for further assessment. Eleven substances were assigned a score of 6; of these, those substances that are readily biodegradable were screened out (DEHP, DEP, DCH and BBP). TMTD was screened out as it is expected to be consumed in the manufacturing process as a sulphur donor and 4-(1-methyl-1-phenylethyl)-N-[4-(1-methyl-1-phenylethyl) phenyl]aniline was also screened out as the scoring for this substance was largely driven by tonnage, there are uncertainties in the hazard dataset for this substance and there is no indication that the UK REACH registration(s) or DUINs for this substance is connected to the production of tyres. Tris(4-nonylphenyl, branched and linear) phosphite (TNPP) with ≥ 0.1% w/w of 4-nonylphenol, branched and linear (4-NP) was screened out at this stage as it does not have a UK REACH registrant or DUIN. The remaining substances with a score of 6 were all screened in for the next stage of the project, resulting in 18 substances for further assessment. In addition, 6PPD-Q and IPPD-Q were also taken forward as oxidation products of 6PPD and IPPD, respectively. Tables 4.3, 4.4, 4.5 and 4.6 include the ‘Of concern’, ‘Of potential concern’, ‘Lower concern’ and ‘Cannot be assessed’ substances, respectively, along with the assigned prioritisation scores. The full prioritisation database is provided in Annex 2.

Table 4.3 Substances assigned to the category 'Of concern' and their quantitative scores

Substance	CAS Number	PBT/vPvB, PMT/vPvM or environmental classification	PBT - Bioaccumulative in Air Breathing Organisms	ED	REACH Tonnage	Percentage in tyres	Total	Qualitative categorisation
t-OP	140-66-9	3	0	2	3	1	**9**	**Of concern**
Zinc oxide	1314-13-2	3	0	0	4	2	**9**	**Of concern**
BTA	95-14-7	4	0	2	2	1	**9**	**Of concern**
DBP	84-74-2	3	0	1	2	2	**8**	**Of concern**
Aniline	62-53-3	3	0	0	4	1	**8**	**Of concern**
6PPD	793-24-8	3	0	1	3	1	**8**	**Of concern**
DPG	102-06-7	3	0	1	3	1	**8**	**Of concern**
DCBS	4979-32-2	4	0	0	2	1	**7**	**Of concern**
TPP	115-86-6	2	0	2	2	1	**7**	**Of concern**
CBS	95-33-0	3	0	0	3	1	**7**	**Of concern**
BENPAT	68953-84-4	2	0	1	3	1	**7**	**Of concern**
MBT	149-30-4	3	0	0	3	1	**7**	**Of concern**
MBTS	120-78-5	3	0	0	3	1	**7**	**Of concern**
IPPD	101-72-4	3	0	1	2	1	**7**	**Of concern**

Table 4.4 Substances assigned to the category 'Of potential concern' and their quantitative scores

Substance	CAS Numbers	PBT/vPvB, PMT/vPvM or env.classification	PBT - Bioaccumulative in Air Breathing Organisms	ED	REACH Tonnage	Percentage in tyres	TOTAL	Qualitative categorisation
DEHP	117-81-7	0	0	1	3	2	**6**	**Of potential concern**
BBP	85-68-7	3	0	1	0	2	**6**	**Of potential concern**
Tris(4-nonylphenyl, branched and linear) phosphite (TNPP) with ≥ 0.1% w/w of 4-nonylphenol, branched and linear (4-NP)	None	3	0	2	0	1	**6**	**Of potential concern**
DEP	84-66-2	0	0	1	3	2	**6**	**Of potential concern**
44PD	101-96-2	2	0	1	2	1	**6**	**Of potential concern**
TBBS	95-31-8	2	0	0	3	1	**6**	**Of potential concern**
DCH, DCHA	101-83-7	3	0	0	2	1	**6**	**Of potential concern**
TMTD	137-26-8	3	0	0	2	1	**6**	**Of potential concern**
7PPD	3081-01-4	2	0	1	2	1	**6**	**Of potential concern**
DPPD	74-31-7	2	0	1	2	1	**6**	**Of potential concern**

Substance	CAS Numbers	PBT/vPvB, PMT/vPvM or env.classification	PBT - Bioaccumulative in Air Breathing Organisms	ED	REACH Tonnage	Percentage in tyres	TOTAL	Qualitative categorisation
4-(1-Methyl-1-phenylethyl)-N-[4-(1-methyl-1-phenylethyl) phenyl]aniline	10081-67-1	2	0	0	3	1	**6**	**Of potential concern**
DIBP	84-69-5	2	0	1	0	2	**5**	**Of potential concern**
Isononylphenol	11066-49-2	2	0	2	0	1	**5**	**Of potential concern**
DPA	122-39-4	3	0	0	1	1	**5**	**Of potential concern**
TMQ	26780-96-1	1	0	0	3	1	**5**	**Of potential concern**
ADPA	68412-48-6	2	0	0	2	1	**5**	**Of potential concern**
mDCHA	7560-83-0	2	0	0	2	1	**5**	**Of potential concern**
UV-928	73936-91-1	2	0	0	2	1	**5**	**Of potential concern**
77PD	3081-14-9	2	0	0	2	1	**5**	**Of potential concern**
DBMC	119-47-1	0	0	1	2	1	**4**	**Of potential concern**
DnOP	117-84-0	1	0	1	0	2	**4**	**Of potential concern**
5-MTBR	136-85-6	2	0	1	0	1	**4**	**Of potential concern**
Cyclohexylamine	108-91-8	0	0	0	2	1	**3**	**Of potential concern**

Substance	CAS Numbers	PBT/vPvB, PMT/vPvM or env.classification	PBT - Bioaccumulative in Air Breathing Organisms	ED	REACH Tonnage	Percentage in tyres	TOTAL	Qualitative categorisation
6-PPDQ	2754428-18-5	2	0	0	0	1	**3**	**Of potential concern**
8PPD	15233-47-3	2	0	0	0	1	**3**	**Of potential concern**
CPPD	101-87-1	2	0	0	0	1	**3**	**Of potential concern**
Ethoxyquin	91-53-2	2	0	0	0	1	**3**	**Of potential concern**
Phenylguanidine	2002-16-6	2	0	0	0	1	**3**	**Of potential concern**
o-MBp24	88-24-4	1	0	0	0	1	**2**	**Of potential concern**

Table 4.5 Substances assigned to the category 'Lower concern' – not taken forward in prioritisation

Substance	CAS number
Stearic acid	57-11-4
MIBK	108-10-1
BTZ, BZT	95-16-9
DHU, DCU	2387-23-7
24MoBT	4225-26-7
MeBT	120-75-2
MeSBT	615-22-5
BTSA	941-57-1
HOBT	934-34-9
DNPD	93-46-9
NCBA	28291-75-0
HMMM	3089-11-0
DPU	102-07-8
Indanone	83-33-0

Table 4.6 Substances assigned to the category 'Cannot be assessed' – a prioritisation score could not be determined based on the available data

Substance	CAS number
2-Benzothiazolesulfenamide	2801-21-0
CPU	886-59-9
DTPD	27417-40-9
IPPD-quinone	68054-73-9

5 Risk-based Prioritisation

18 substances were selected from the hazard prioritisation exercise as detailed in Section 4. These substances were then further assessed in a risk-based prioritisation using the EA model for tyre particle leaching (EA, Unpublished) and the outputs from this were used to populate the EUSES model (ECB, 2004). The para-PPD degradation products 6PPD-Q and IPPD-Q were also assessed on the basis of specific concerns in the scientific literature about toxicity to aquatic organisms (e.g. (Tian *et al.*, 2021)). The EUSES model was used to calculate PECs that are compared to PNECs in order to quantify potential risk by the calculation of RCRs. The RCRs were used to generate a ranking based on risk to the aquatic environment in the UK, for comparison with the hazard prioritisation exercise. Additionally, the PECs calculated by EUSES are compared to the EA's monitoring data for watercourses in England.

5.1 Use of EA model for tyre particle leaching

As part of the EA's Tyre Exposure Project an exposure model was developed to estimate the mass of TWP released from the UK Strategic Road Network (SRN) via compartmentalising the network into Motorways, Rural and Urban Roads. The calculated mass is then partitioned to air, soil (both roadside verge and the wider environment) and water (wastewater and surface water). Emissions to air are ultimately expressed as contributing to emissions to soil. The model, using literature data and a number of assumptions, then estimates the mass and partitioning of leached chemicals from the TWP for both local and regional scenarios.

Values were inputted for parameters such as road length, number and type of vehicles and road type (based on DfT (2022a, 2022b, 2022c); accessed 13th June 2024)). These data are then used in conjunction with emission rates sourced from literature to calculate the TWP rubber particle mass that is released to the environment on an annual basis. The model was pre-populated by the EA to calculate a "regional" release mass of particulate and leachate.

The mass of released tyre rubber particles is used to calculate the amount of chemical leached using a set of chemical-specific parameters. The chemical is then partitioned to environmental compartments depending on whether the source is set to Motorway, Rural or Urban roads. These estimations are made using a number of generic assumptions due to the limited availability of chemical-specific leaching data (see EA (Unpublished), Section 3.3.3).

Several conservative assumptions were considered in the initial, worst case scenario modelling:

- the concentration of the substance used in tyre manufacture and the concentration in tyres after manufacture are assumed to be the same (i.e. no consumption of additive during manufacture);
- it was considered that each substance was present at the total concentration of the chemical class, e.g. all antioxidants/antiozonants at 2% and vulcanising agents at 1% (see Table 28 in EA (Unpublished)). This assumption does not consider the presence of multiple chemicals of the same chemical class; and
- substances were not considered to transform or degrade during use of the tyre. Degradation products were considered as specific tyre additives present at the same concentration as their parent products.

A further ‘refined’ scenario was characterised by a less conservative value for the concentration of each additive used in tyre manufacture; this was based on the highest measured concentration for any individual substance in each class of additive as detailed in Table 2.1. The maximum concentrations used in the refined assessment were as follows:

- plasticisers: 0.0059% (based on 59 mg/kg DEHP);
- vulcanising agents: 0.065% (based on 650 mg/kg MBT);
- antioxidants/ozonants: 0.12% (based on 1,200 mg/kg 6PPD); and
- zinc oxide measured at a maximum concentration of 1.05% (10,464 mg/kg).

The model calculated an overall annual mass of TWP released in the UK and the mass released from Motorway, Rural and Urban roads to soil and watercourses. TWP and leachate from Motorway and Rural roads are pre-processed by the model regarding wastewater treatment and removal by partitioning. However, releases from Urban roads are not considered in this way so need to be processed to determine removal during wastewater treatment, estimating the amount partitioning to sludge and the subsequent leachate mass remaining.

5.1.1 Modelling of partitioning in wastewater treatment

The SimpleTreat model (v3.1) was used to determine the removal of substances in leachate releases from Urban roads and the amount partitioning to sludge that may then be applied to agricultural soils (Struijs, 2014). The SimpleTreat model is used to estimate the fraction of a substance entering a hypothetical wastewater treatment works (WwTW) that will be directed to air, water and sludge or degraded (Struijs *et al.*, 1991). SimpleTreat is used as a component of the EUSES model, so the outputs are compatible with the later stages of regional exposure modelling using EUSES. No comparison of SimpleTreat outputs with regulatory assessments has been carried out, the outputs of the model are summarised below without further editing.

The removal efficiency of zinc leached from zinc oxide is assumed to be 74% based on measured influent and effluent concentrations at WwTWs in Europe (JRC, 2010). It is assumed that all removal is due to sorption to particulate matter, i.e. sludge.

Table 5.1: Predicted removal efficiency of tyre additives in a WWTW using SimpleTreat

Substance	Overall % removal in WwTW	% to sludge	% to air
t-OP	78.6	45.0	19.2
ZnO	74.0	74.0	0
BTA	0.31	0.192	0.12
DBP	90.5	29.2	0.0685
Aniline	87.3	0.0652	0.046
6PPD	48.2	47.3	0.901
DPG	87.4	1.07	2.80×10^{-10}
DCBS	84.8	84.5	0.277
TPP	64.1	41.0	0.103
CBS	60.8	60.7	0.0254
BENPAT	50.5	17.1	0.121
MBT	1.42	1.42	7.1×10^{-4}
MBTS	39.8	39.8	0.00102
IPPD	2.89	2.687	0.204
44PD	14.0	13.4	0.563
TBBS	7.82	7.77	0.0526
7PPD	67.0	66.9	0.0642
DPPD	8.6	8.166	0.433
6PPD-Q	14.8	14.8	8.5×10^{-5}
IPPD-Q	1.9	1.90	1.3×10^{-5}

5.2 Regional exposure modelling

5.2.1 EUSES model inputs

Regional exposure modelling to estimate the average concentration of tyre additive substances in different environmental compartments (i.e. water, sediment and soil) was undertaken using EUSES version 2.1.2. EUSES is a commonly used tool for the regulatory risk assessment of chemicals within Europe that uses various steady-state distribution models representing different geographical scales, i.e. local, regional and continental. The generic default region within EUSES is taken to be representative of a defined area containing a proportion of the European population and is considered to be broadly representative for Great Britain (GB). The fraction of the main local source was set to one as GB is essentially set as the region. The number of emission days was set to 365 to reflect the ubiquitous use nature of tyres and ongoing leaching.

Important inputs for regional exposure modelling are the total annual release of leachate for each substance (in terms of tonnes per annum) and the proportion of this emitted to individual environmental compartments. These values were calculated from the output of the tyre model (with adjustments for the effect of wastewater treatment as detailed in Section 5.1.1) and are presented in Table 5.2.

Table 5.2: Annual mass of leachate released from TWP (worst case and refined scenarios) and fractions released to environmental compartments

Substance	Annual release (tpa)		Release factors (%)		
	Worst case	Refined	Water	Roadside soil	Agricultural soil
t-OP	99.87	11.98	10.47	55.79	30.76
ZnO	2.00	0.053	11.09	55.79	32.07
BTA	199.75	11.98	51.39	31.00	12.36
DBP	99.87	0.80	8.88	55.79	26.08
Aniline	199.75	11.98	70.19	6.20	2.48
6PPD	199.75	11.98	14.54	55.79	28.62
DPG	99.87	2.01	39.73	31.00	12.46
DCBS	99.87	2.01	9.64	55.79	13.81
TPP	199.75	11.98	12.42	55.79	27.67
CBS	99.87	2.01	12.86	55.79	30.30
BENPAT	199.75	11.98	44.67	31.00	14.61
MBT	99.87	2.01	51.24	31.00	12.50
MBTS	99.87	2.01	15.67	55.79	7.78
IPPD	199.75	11.98	51.05	31.00	12.70
44PD	199.75	11.98	49.57	31.00	14.18
TBBS	99.87	2.01	50.39	31.00	13.36
7PPD	199.75	11.98	12.03	55.79	31.13
DPPD	199.75	11.98	50.28	31.00	13.46
6PPD-Q	199.75	11.98	49.46	31.00	14.29
IPPD-Q	199.75	11.98	51.18	31.00	12.57

EUSES was also populated for each substance with values collected for the assessments detailed in Sections 3 and 4, i.e. for physio-chemical parameters, partition coefficients and bioconcentration factors, biodegradation characteristics and PNECs. Aside from the specific physio-chemical parameter values for each substance, the default EUSES parameters values were used and no adjustment was made to reflect GB-specific values for environmental parameters.

5.1.2 Assessment of zinc oxide

The EUSES model was developed for the assessment of organic substances and cannot be run without the inclusion of a log K_{OW} value, which is not relevant for inorganic substances such as zinc oxide.

This section details the generation of a log K_{OW} for zinc oxide; the ECHA (2012) Guidance on Environmental Exposure Assessment R.16 (v2.1) contains all of the required equations and calculation details (these were removed from subsequent versions).

The log K_{OW} value is generated by first calculating a value a wet-weight soil partitioning coefficient from the dry-weight (dw) coefficient. This is then used to calculate the partition coefficient based on the fraction of organic carbon in the relevant medium. The partition coefficient can be corrected to account for the moisture content. Lastly, the K_{OC} Is transformed and converted to a log K_{OW} based on a QSAR. Partitioning to the air is ignored due to the extremely low volatility of inorganic substances such as zinc oxide.

The partition coefficient reported on a dry weight basis ($K_{P\,dw}$, reported in units of L/kg) is first corrected for the moisture content of the soil, sediment, or suspended matter according to Equation 1 (ECHA, 2012) .

$$\boldsymbol{K_{P\,ww} = F_{Water} + F_{Solid} \times \left(\frac{K_{P\,dw}}{1000}\right) \times D_{Solid}}$$

Equation 1 - Correction of dw partition coefficient to account for moisture content

The wet weight partition coefficient ($K_{P\,ww}$) is then converted to K_{OC} according to Equation 2 (ECHA, 2012).

$$\boldsymbol{K_{OC} = \frac{K_{P\,ww}}{F_{OC}}}$$

Equation 2 - Calculation of an organic carbon normalised partition coefficient from the wet weight partition coefficient

The K_{OC} is then log transformed and converted into an equivalent log K_{OW} based on a [non-hydrophobics] QSAR (ECB, 2003).

$$\boldsymbol{\log K_{OW} = \frac{\log K_{OC}}{0.52} - 1.02}$$

Equation 3 - Calculation of K_{OW} from the K_{OC}

Explanation of the variables used in Equation 1, 2 & 3		Units	Source
$K_{P\ ww}$	Wet weight solids-water partition coefficient	L/kg	
$K_{P\ dw}$	Dry weight solids-water partition coefficient	L/kg	
F_{water}	Fraction of water in compartment	m^3/m^3	Table R16-9 (ECHA, 2012)
F_{solid}	Fraction of solids in compartment	m^3/m^3	Table R16-9 (ECHA, 2012)
D_{solid}	Density of the solid phase	kg/m^3	
F_{OC}	Fraction of organic carbon in compartment	kg/kg	Table R16-9
K_{OC}	Organic carbon normalised partition coefficient		
K_{OW}	Octanol water normalised partition coefficient		

The resulting equivalent log K_{OW} value can then be used as an input parameter for EUSES calculations. Different equivalent log K_{OW} values may be required to make accurate predictions for different environmental compartments but the value for soil was selected as the most appropriate for this assessment. The log K_p of 3.24 is different from the value of 2.2 used in the European Union Risk Assessment Report (RAR) for Zinc (JRC, 2010), which is based on experimental data. The resulting log K_{OW} used in this report is therefore higher than would be calculated using the RAR value. It was beyond the scope of the report to consider this further.

Table 5.3: Summary of input parameters and calculated equivalent log K_{OW} values

Parameter	Units	Soil	Sediment	Freshwater Suspended Sediment	Marine Suspended Sediment
Log K_p	-	3.24	3.49	4.67	4.01
$K_{p\ dw}$	L/kg (dw)	1738	3090	46774	10233
$K_{p\ ww}$	L/kg (ww)	1158	1545	187090	40928
Koc	L/kg	57920	30901	1870905	409280
log K_{OC}	-	4.76	4.49	6.27	5.61
log K_{OW}	-	**7.20**	6.67	10.10	8.83

5.3 Regional exposure modelling results and risk assessment

The PECs calculated for each environmental compartment using the worst case and refined assumptions for concentration of the tyre additives in TWP are detailed in Annex 3. RCRs for each substance, calculated from a comparison of PEC to PNEC for water, sediment and soil, are detailed for the worst case and refined scenarios in Tables 5.4 and 5.5, respectively. RCRs exceeding 1, indicating the potential for unacceptable levels of risk, are highlighted in red.

RCRs could be calculated for 19 of the 20 tyre additives and degradation products for which exposure assessment was conducted; no PNECs were identified for

IPPD-Q. Under the worst case scenario, RCRs above 1 were calculated for 14 out of 19 substances; under the refined scenario this was 5 out of 19. Very high RCRs were calculated for DCBS and MBTS (1500 and 210, respectively, under the worst case scenarios) but these should be treated with caution as the robustness of the QSAR-based PNECs used in the risk assessment, taken from the NORMAN database, was not investigated.

Table 5.4: Regional RCRs calculated from worst case scenario of leachate release volume, values ≥1 highlighted

Substance	Freshwater	Marine water	Freshwater sediment	Marine sediment	Agricultural Soil
t-OP	0.066	0.0057	0.0086	0.0024	0.0018
ZnO	4.95×10^{-5}	1.22×10^{-5}	4.57×10^{-4}	4.95×10^{-5}	8.00×10^{-5}
BTA	0.042	0.04	0.042	0.04	0.023
DBP	0.0095	0.0086	0.0095	0.0063	0.0084
Aniline	**1.45**	**1.31**	0.413	0.326	0.0026
6PPD	**3.72**	**3.52**	**5.96**	**4.77**	0.148
DPG	0.014	0.013	0.024	0.016	5.10×10^{-4}
DCBS	**15.1**	0.257	**1500**	**4.96**	-
TPP	**1.53**	**1.48**	**2.57**	**2.15**	0.312
CBS	**1.48**	**1.44**	**2.84**	**2.35**	0.04
BENPAT	**4.31**	**4.32**	**2.72**	**2.65**	0.048
MBT	0.60	0.58	**1.77**	**1.43**	0.86
MBTS	**210**	**0.0521**	**6.24**	**5.31**	-
IPPD	**13.8**	**13.3**	**73.8**	**48**	**45.9**
44PD	**1.11**	**1.07**	**2.17**	**1.83**	0.0201
TBBS	**10.9**	**10.5**	**11.6**	**11.1**	0.0221
7PPD	0.163	0.223	**11.7**	**10.4**	0.662
DPPD	0.0857	0.0861	**68.4**	**67.1**	**15.6**
6PPD-Q	**49.2**	-	**80.6**	-	-
IPPD-Q	RCRs could not be calculated due to absence of a PNEC				

Table 5.5: Regional RCRs calculated from refined scenario of leachate release volume, values ≥1 highlighted

Substance	Freshwater	Marine water	Freshwater sediment	Marine sediment	Agricultural soil
t-OP	0.00792	0.000684	0.00103	2.88×10^{-4}	2.16×10^{-4}
ZnO	1.30×10^{-5}	3.20×10^{-6}	1.20×10^{-4}	1.30×10^{-5}	2.10×10^{-5}
BTA	0.00252	0.00240	0.00252	0.00240	0.00138
DBP	7.61×10^{-5}	6.89×10^{-5}	7.61×10^{-5}	5.05×10^{-5}	6.73×10^{-5}
Aniline	0.087	0.079	0.025	0.020	1.56×10^{-4}
6PPD	0.223	0.211	0.357	0.286	0.00888
DPG	2.82×10^{-4}	2.62×10^{-4}	4.83×10^{-4}	3.22×10^{-4}	1.03×10^{-5}
DCBS	0.304	0.0052	**30.2**	0.0998	-
TPP	0.092	0.089	0.154	0.129	0.019
CBS	0.0298	0.0290	0.0572	0.0473	0.0008
BENPAT	0.26	0.26	0.16	0.16	0.003
MBT	0.012	0.012	0.036	0.029	0.0173
MBTS	**4.2**	0.0010	0.126	0.107	-
IPPD	0.83	0.80	**4.43**	**2.88**	**2.75**
44PD	0.0223	0.0215	0.0437	0.0368	4.0×10^{-4}
TBBS	0.65	0.63	0.70	0.67	0.00133
7PPD	0.010	0.013	0.702	0.624	0.040
DPPD	0.005	0.005	**4.10**	4.024	0.936
6PPD-Q	**2.95**	-	**4.83**	-	-
IPPD-Q	RCRs could not be calculated due to absence of PNEC				

5.4 Risk-based prioritisation

One of the primary objectives of this project was the risk-based prioritisation of tyre additives that had already been selected from a mainly hazard-based assessment. Risk-based ranking of the 'of concern' and 'potential concern' substances identified from the hazard-based prioritisation is presented in Table 5.6. Ranking is from high to low for the RCRs calculated during the refined assessment and the most sensitive environmental compartment identified by the risk assessment is also highlighted (i.e. the compartment in which the highest RCR was calculated).

Table 5.6: Risk-based ranking of tyre additives based on regional RCR values calculated by EUSES, values above 1 highlighted

Substance	Highest RCR (worst case scenario)	Highest RCR (refined scenario)	Sensitive compartment
DCBS	**1500**	**30**	Freshwater sediment
MBTS	**210**	**4.2**	Freshwater
6PPD-Q	**81**	**4.8**	Freshwater sediment
IPPD	**74**	**4.4**	Freshwater sediment
DPPD	**68**	**4.1**	Freshwater sediments
7PPD	**12**	0.70	Freshwater sediments
44PD	**12**	0.70	Freshwater sediments
6PPD	**6.0**	0.36	Freshwater sediments
BENPAT	**4.3**	0.26	Freshwater and marine water
CBS	**2.8**	0.057	Freshwater & marine sediments
TPP	**2.6**	0.15	Freshwater & marine sediments
TBBS	**2.2**	0.044	Freshwater & marine sediments
MBT	**1.8**	0.036	Freshwater & marine sediments
Aniline	**1.5**	0.087	Freshwater and marine water
t-OP	0.066	0.0079	Freshwater
BTA	0.042	0.0025	Freshwater & freshwater sediment
DPG	0.024	4.8×10^{-4}	Freshwater sediment
DBP	0.0095	7.6×10^{-5}	Freshwater & freshwater sediment
ZnO	5.0×10^{-5}	1.3×10^{-5}	Freshwater, & marine sediment

A comparison of the output from the hazard and risk-based prioritisation is presented in Table 5.7 – hazard-based rankings were ordered, where possible, with weighting given to hazard if scores were tied.

Table 5.7: Risk and hazard-based prioritisation of tyre additives

Substance	Risk-based ranking	Hazard-based ranking		
		Ranking	Score	Status
DCBS	*1*	8	7	Of Concern
6PPD-Q	2	18	3	Of Potential Concern
IPPD	3	11	7	Of Concern
MBTS	*4*	11	7	Of Concern
DPPD	5	15	6	Of Potential Concern
7PPD	6	15	6	Of Potential Concern
44PD	7	15	6	Of Potential Concern
6PPD	8	4	8	Of Concern
BENPAT	9	11	7	Of Concern
TPP	10	8	7	Of Concern
CBS	11	8	7	Of Concern
Aniline	12	7	8	Of Concern
TBBS	13	17	6	Of Potential Concern
MBT	14	11	7	Of Concern
t-OP	15	2	9	Of Concern
BTA	16	1	9	Of Concern
DPG	17	4	8	Of Concern
DBP	18	4	8	Of Concern
ZnO	19	3	9	Of Concern

Note: Grey shading indicates uncertainty within the identified PNECs

Strikingly different results were generated by the hazard and risk-based prioritisations. The hazard-based assessment generally gave the highest ranking to substances well known as environmental pollutants, e.g. t-OP, zinc oxide and BTA. In contrast, these substances came near the bottom of the risk-based prioritisation (pink shading) that gave the highest rankings to the vulcanising agents DCBS and MBTS, and the PPD antiozonants and their degradation products. This difference in the hazard prioritisation rankings is likely due to more information being available for the well-known and better characterised environmental pollutants compared to the lesser-known substances primarily used as tyre additives. The amount of toxicity data affects the size of the assessment factor used to derive the PNEC, resulting in potentially low PNECs when uncertainty is high. Substances which have been classified for toxicity to the aquatic environment were flagged by the hazard-based assessment, which indicates the validity of the approach, but did not discriminate the degree of toxicity.

The results for DCBS and MBTS (grey shading) should be treated with caution as there is uncertainty around the PNECs identified for these substances. The PNECs were predicted by QSAR and assessment factors of 1,000 have been applied in the derivation, making them very conservative. The risk-based approach is based on a series of worst-case assumptions, so is also conservative, particularly for transformation products. Based on their function, however, it is expected that the greater part of the PPDs would be become available for transformation eventually.

Sediment is identified as the most sensitive compartment for 15 out 18 substances and is likely to be the ultimate sink of TWP as they will separate out of the water column based on their average density (≥1 g/cm^3) (Klockner *et al.*, 2021a; Klockner *et al.*, 2021b; Parker-Jurd *et al.*, 2024).

Although soil, especially roadside soil, is expected to receive the majority of the inputs from tyre rubber, comparison of the modelled PECs with soil PNEC values did not generally indicate a risk. Two exceptions were IPPD (RCR = 45.9) and DPPD (RCR = 15.6) based on the PNEC from the ECHA registration dossiers. In the refined scenario, the RCR for IPPD is 2.75 and 0.94 for DPPD.

It should be noted that the EUSES modelling was undertaken to provide a standardised way for the relative risk to be ranked and no adjustment was made for GB-specific parameters. As such, the outputs should not necessarily be interpreted as indicating a risk that is not adequately controlled.

5.5 Comparison of PECs to monitoring data

The PECs calculated from the exposure modelling can be compared to monitoring data from the EA's screening and Water Information Management System (WIMS, Environment Agency (2024)) monitoring databases (these data are semi- and fully quantitative, respectively). The results are summarised in Tables 5.8 and 5.9 for freshwater and saline waters, respectively.

Monitoring data are only available for a limited number of the substances for which exposure modelling was performed. Apart from 6PPD and BENPAT, these are generally well-known pollutants that will have many other sources of emission to the environment in addition to their use as tyre additives. For example, BTA is an ingredient in dishwasher tablets, TPP has several uses that may lead to dispersive emissions (EA, 2009), and there are numerous sources of zinc (including natural sources). In addition, the semi-quantitative nature of the screening data means the values are only indicative, and should not be interpreted as actual concentrations. Finally, EA sampling locations do not necessarily correspond to areas with high levels of road runoff. For example, many locations are in rural catchments. Comparison between measured concentrations and PECs is also confounded by potential limitations in analytical sensitivity and limits of detection (LOD).

This makes any meaningful comparison between the PECs and measured concentrations extremely difficult for these substances. Where measured concentrations are much higher than the PECs in both types of waters, this is likely due to additional sources. For a few substances such as DPG, the mean measured concentrations are comparable to the PECs, which could indicate that tyre additives may be the major source of emission to the environment. However, this would require further investigation.

Table 5.8: Comparison of EUSES PECs to EA freshwater monitoring data

Substance	PEC (µg/L)		Positive detects	Monitoring data (µg/L)		
	Worst case	Refined		Mean	Minimum	Maximum
t-OP*	0.0664	0.00796	33	0.104	0.01	1.4
ZnO* (as zinc)	0.0015	3.95 $\times 10^{-4}$	3555	376	0.05	49000
BTA†	0.406	0.0244	44	20.35	0.5	442
DBP†	0.0949	0.00076	266	4.88	0.02	170
Aniline†	1.45	0.0870	198	8.85	0.002	850
DPG†	0.434	0.00873	909	0.025	0.0004	0.57
TPP†	0.740	0.0444	93	0.08	0.0034	1.00
6PPD†	1.38	0.0828	0	ND	ND	ND
BENPAT†	1.98	0.119	0	ND	ND	ND

Note: ND – not detected.
*WIMS data (targeted monitoring for regulatory assessment).
†Non-targeted screening data. As only positive detections are reported, the detection frequency is unknown.

Table 5.9: Comparison of EUSES PECs to EA saline waters monitoring data

Substance	PEC (µg/L)		Positive detects	Monitoring data (µg/L)		
	Worst case	Refined		Mean	Minimum	Maximum
t-OP*	0.0057	6.86 $\times 10^{-4}$	14	0.29	0.02	3.1
ZnO* (as zinc)	1.41 $\times 10^{-4}$	3.69 $\times 10^{-4}$	461	4.52	0.4	69
BTA†	0.0392	0.00235	3	0.73	0.6	1
DBP†	0.0086	6.89 $\times 10^{-5}$	77	4.86	1	27.41
Aniline†	0.131	0.00786	10	0.023	0.04	0.072
DPG†	0.0393	7.9 $\times 10^{-4}$	140	0.01	0.041	0.21
TPP†	0.0714	0.00428	3	0.047	0.017	1

Note: *WIMS data (targeted monitoring for regulatory assessment).
†Non-targeted screening data. As only positive detections are reported, the detection frequency is unknown.

National Highways (2023a, 2023b, 2023c) reported the results of an initial survey of chemical pollution associated with the SRN. The study involved a limited number of samples but detected 42 substances above the limits of detection. NH detected BTA, Zn, t-OP, 6PPD and DPG, which are all substances taken forward for risk-based prioritisation in this study, making a comparison possible between the PECs from this report and measured environmental concentrations (MECs).

Mean MECs of BTA in surface water runoff (2.8 mg/L) and motorway drainage ponds (0.46 mg/L) were at least four orders of magnitude higher than the worst case surface water PEC; mean MECs in sediment (3.8 mg/kg) were also several orders of magnitude higher than the worst case PEC for this compartment.

The discrepancy between the PECs and the MECs for BTA may be in part due to other sources, but more likely due the analytical methods employed (pyrolysis gas chromatography-mass spectrometry (py-GC-MS), whereby the tyre particles were pyrolysed, thus representing the concentration in TWP and not the leachate.

The mean MECs of DPG (2.24 µg/L) and dissolved Zn (62.12 µg/L) exceeded the worst case PECs by between one and five orders of magnitude respectively, although the concentrations of Zn are likely to be attributable to additional sources other than tyres.

The mean MECs of t-OP (0.027 µg/l) and 6PPD (1.16 µg/L) were within the range of PECs from the worst case and refined scenarios.

BTSA, CHA, CPU, DCU, HMMM, HOBT, 1-indanone and MeSBT were also detected by NH in one or more samples, but these substances screened as ‘lower concern’ or ‘could not be assessed’ for the purposes of this prioritisation and so were not modelled in EUSES, meaning comparison of PECs and MECs cannot be made.

The NH results are likely to be more relatable to the PECs derived in this report than the EA monitoring data, given the proximity of the sampling locations to major roads. EQS/PNEC exceedances were reported by NH for dissolved Zn, t-OP and DPG. It is beyond the scope of this report to review the findings in detail, as the selected PNECs may be different from the ones used in this study, and some of the chemicals detected are not necessarily tyre additives (e.g. other sources could include road infrastructure, fuels, lubricants and brake wear particles).

Other sources notwithstanding, compared to the EA and NH MECs, the PECs were generally lower indicating potential underestimation by the model and the need for refinement, particularly around the concentration in the tyre rubber. It is notable that some of the priorities identified from the risk ranking were either not detected by NH and, conversely, some substances with low RCRs (e.g. DPG) had reported PNEC exceedances. This underlines the points that this study is a relative ranking exercise, rather than a formal risk assessment, and an assessment of reliability should be made of any PNECs that might be used in this regard.

Comparison between studies could be facilitated by the reporting of CAS and/or EC numbers as synonyms may differ between studies and substances may have one or more common or IUPAC names.

6 Conclusions and recommendations

6.1 Summary and conclusions

Both hazard and risk-based prioritisations were undertaken for a variety of tyre additives. 61 substances (including a small number of transformation products) were selected for hazard-based assessment based on their previous consideration in assessments performed by regulators and scientific researchers.

Substances were prioritised using a quantitative scoring system based on hazard (environmental hazard classification, PBT/vPvB, PMT/vPvM and ED) and exposure potential (REACH registration tonnages and percentages of substance used in tyres). Qualitative categories were then assigned based on the scores, as follows: ‘Of concern’ (14 substances), ‘Potential concern’ (29 substances), ‘Lower concern’ (14 substances) and ‘Could not be assessed’ (4 substances without sufficient data for assessment). The substances with the highest quantitative scores (indicating most concern) were t-OP, zinc oxide and BTA, all with nine points out of the possible total of thirteen.

Based on the prioritisation process, 18 substances were taken forward for further risk-based assessment. These included all of the ‘Of concern’ substances and some of the highest scoring substances from the ‘Of potential concern’ category, selected based on expert judgement. In addition, 6PPD-Q and IPPD-Q were also taken forward as potentially hazardous oxidation products of 6PPD and IPPD, respectively.

The risk assessment was performed using EA’s draft TWP exposure scenario combined with the EUSES model. Tyre additives were ranked according to the highest predicted risk for environmental compartments such as water, sediment and soil. The substances with the highest predicted risks were DCBS, MBTS, 6PPD-Q and IPPD. The results for DCBS and MBTS should be treated with caution as there is uncertainty around the aquatic PNECs identified for these substances. Apart from these two substances, six out of the top eight substances in the risk-based prioritisation are PPDs or associated transformation product. Aside from DCBS, the highest RCR was calculated for the transformation product 6PPD-Q. This RCR was more than 10 times higher than that calculated for the parent compound, 6PPD, indicating that transformation products may present a greater risk to the aquatic environment, based on the assumptions used in the modelling, as suggested previously (see EA (Unpublished); Khan *et al.* (2024); Tian *et al.* (2021)). However, this would need to be confirmed by a review of the ecotoxicity data used to derive the respective PNECs and assessment of evidence for the occurrence of these substances in GB waterways. IPPD and DPPD were predicted to be a risk to soil and are also PPDs. The modelling was undertaken as a relative ranking exercise for prioritisation purposes and does not mean that chemicals found in tyres are causing an actual environmental risk in GB that is not adequately controlled.

6.2 Recommendations

- A key requirement for more refined and robust risk assessment is to obtain more accurate data on the concentrations of additives in tyres or TWP and their leaching rates.

- Detailed assessment could be undertaken for the highest priority substances, addressing:

    - the reliability of the supporting ecotoxicological data (some of the larger RCRs may be due to the use of PNECs based on limited toxicity data with the application of large assessment factors);

    - degradation products that may be more toxic than the parent compounds (e.g. using software to predict the most likely degradation pathways); and

    - the potential for mixture effects based on similarity of mode of action.

In particular, a group assessment of the PPDs might be beneficial given the proportion of substances from this group of chemicals that were identified as a priority based on relative risk.

- Monitoring could be undertaken for the substances ranked highest by the risk-based prioritisation (i.e. those with predicted RCRs above 1), with a focus on the environmental compartments identified as most sensitive for each substance. A significant number of substances were identified as presenting the greatest risk to sediment, for which monitoring data are rarely available. This should be considered in any future monitoring project. Soil monitoring could also be considered.

- Substances that were not taken forward into the risk-based prioritisation, particularly those of ‘lower concern’, could be revisited if further relevant data become available in future. The report findings could also be reviewed as and when the draft exposure scenario for TWP is refined, or more comprehensive relevant monitoring data become available.

- This report covers potential environmental concerns only. Some tyre additives have human health hazard classifications and there is potential for human exposure from the release of TWP. This may be a gap in terms of priority setting, which could be considered further by interested stakeholders.

- Comparison between studies could be facilitated by the reporting of CAS and/or EC numbers as synonyms may differ between studies and substances may have one or more common or IUPAC names.

7 Glossary

BCF	Bioconcentration factor
BTMA	British Tyre Manufacturers' Association
CAS	Chemical Abstracts Service
CLP	Classification, Labelling and Packaging
DUINS	Downstream user import notifications
DW	Dry weight
EA	Environment Agency
EC	European Community number
ECHA	European Chemicals Agency
ED	Endocrine disrupting
EQS	Environmental Quality Standard
EUSES	European Union System for the Evaluation of Substances
GB	Great Britain
HE	Highways England
IUPAC	International Union of Pure and Applied Chemistry
LOD	Limit of detection
K_{OA}	Octanol-air portioning coefficient
K_{OC}	Organic carbon-water partitioning coefficient
K_p	Partitioning coefficient
MCL	Mandatory Classification and Labelling
MEC	Measured environmental concentration
PACT	Public activities co-ordination tool
PBT	Persistent, bioaccumulative and toxic
PEC	Predicted environmental concentration
PEWS	Prioritisation and early warning system
PMT	Persistent, mobile and toxic
PNECs	Predicted no effect concentration
PPD	Phenylenediamine
py-GC-MS	Pyrolysis gas chromatography-mass spectrometry
QSAR	Quantitative structure-activity relationship
RCR	Risk characterisation ratio
REACH	Restriction, Evaluation, Authorisation and Restriction of Chemicals
SMILES	Simplified Molecular Input Line Entry System
SVHC	Substance of Very High Concern
TWP	Tyre wear particle
UK	United Kingdom
US EPA	United States Environmental Protection Agency
vPvB	Very persistent very bioaccumulative
vPvM	Very persistent very mobile
WW	Wet weight
WFD	Water Framework Directive

WwTW	Wastewater treatment works

Chemicals

24MoBT	2-(4- Morpholinyl)-benzothiazole
44PD	N,N'-Di-sec-butyl-p-phenylene-diamine
5-MTBR	5-Methyl-1H-benzotriazole
6PPD	N-(1.3-Dimethyl-butyl)-N′-phenyl-p-phenylene-diamine
6PPD-Q	6PPD-quinone
77PD	N,N’-Bis(1,4-Dimethyl-pentyl)-p -phenylenediamine
7PPD	N-(1,4-Dimethyl-pentyl)-N’-phenylbenzene-1,4-diamine
8PPD	N-(1-Methyl-heptyl)-N′-phenyl-p-phenylene-diamine
ADPA	Acetone diphenylamine condensate
BENPAT	1,4-Benzene-diamine, N,N'-mixed Ph and tolyl derivs.
BBP	Benzyl butyl phthalate
BTA	1H-Benzotriazole
BTSA	Benzothiazole-2-sulfonic acid
BTZ or BZT	Benzothiazole
CBS	N-Cyclohexyl-benzothiazol-2-sulfenamide
CHA	Cyclohexylamine
CPU	Cyclohexyl-3-phenylurea
CPPD	N-Phenyl-N′-cyclohexyl-p-phenylene-diamine
DBMC	6,6’-Di-tert-butyl-2,2’-methylenedi-p-cresol
DBP	Di-n-butylphthalate
DCBS	N,N-Dicyclohexyl-benzothiazole-2-sulfenamide
DCHA	Dicyclohexyl-amine
DCU or DHU	1,3-Dicyclohexyl-urea
DiBP	Diisobutyl phthalate
DEHP	Di(2-ethylhexyl) phthalate
DEP	Diethyl phthalate
DNPD	N,N′-Di-2-naphthyl-p-phenylene-diamine
DOP	Dioctyl phthalate
DPA	Diphenylamine
DPG	Diphenyl guanidine
DPPD	N,N′-Diphenyl-p-phenylene-diamine
DPU	Diphenyl urea
DTPD	N,N′-Di(ortho-tolyl)-p-phenylene-diamine
HMMM	Hexa(methoxy-methyl)melamine
HOBT	Hydroxybenzo-thiazole
IPPD	N-Isopropyl-N′-phenyl-1,4-phenylene-diamine
IPPD-Q	IPPD-quinone
MBTS	Di(45-benzothiazole-2-yl) disulfide
MBT	2-Mercapto-benzothiazole
mDCHA	N-Methyl-dicyclo-hexylamine
MeBT	2-Methylbenzo-thiazole

MeSBT	2-Methylthio-benzothiazole
MIBK	Methyl isobutyl ketone
NCBA	N-Cyclohexyl-2-benzothiazol-amine
o-MBp24	2,2′-Methylene-bis(4-ethyl-6-*tert*-butylphenol)
PG	Phenylguanidine
TBBS	N-tert-Butylbenzo-thiazole-2-sulfenamide
TMTD	Tetramethyl thiuram disulfide
TMQ	2,2,4-Trimethyl-1,2-Dihydro-quinoline polymer
t-OP	4-tert-Octylphenol
TPP	Triphenyl phosphate
UV-928	2-(2H-Benzotriazol-2-yl)-6-(1-methyl-1-phenylethyl)-4-(1,1,3,3-tetra-methylbutyl)-phenol
ZnO	Zinc oxide

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Annex 1: Source documents for selected substances (Excel spreadsheet)

Annex 2: Hazard-based prioritisation (Excel spreadsheet)

Annex 3: Regional PECs calculated by EUSES

Table A3.1: Regional PECs calculated from worst case scenario of leachate release volume

Substance	Regional PECs				
	Freshwater (µg/L total)	Marine water (µg/L total)	Freshwater sediment (mg/kg ww)	Marine sediment (mg/kg ww)	Agricultural Soil (mg/kg ww)
t-OP	0.0664	0.00572	0.00867	0.000637	0.00367
ZnO	0.0015	1.41×10^{-4}	0.0176	0.0022	0.0073
BTA	0.406	0.0392	0.0099	0.00094	0.0034
DBP	0.0949	0.0086	0.0027	0.000163	0.000372
Aniline	1.45	0.131	0.0138	0.00106	7.49×10^{-5}
6PPD	1.38	0.013	0.142	0.0114	0.215
DPG	0.434	0.0393	0.0131	0.00085	0.00018
DCBS	0.338	0.0319	0.672	0.0649	0.606
TPP	0.74	0.0714	0.08	0.00653	0.00771
CBS	1.49	0.144	0.133	0.0092	0.111
BENPAT	1.98	0.19	3.63	0.354	0.0424
MBT	2.40	0.232	0.0565	0.00467	0.0204
MBTS	1.46	0.141	0.298	0.254	0.086
IPPD	3.88	0.374	0.128	0.0104	0.0405
44PD	3.28	0.0315	0.058	0.00483	0.0249
TBBS	2.22	0.214	0.0377	0.00318	0.0144
7PPD	2.32	0.225	1.08	0.0976	0.957
DPPD	2.68	0.256	5.35	0.525	0.989
6PPD-Q	4.69	0.454	0.405	0.033	0.142
IPPD-Q	4.77	0.462	0.259	0.0209	0.0834

Table A3.2: Regional PECs calculated from refined scenario of leachate release volume

Substance	Regional PECs Freshwater (µg/L total)	Marine water (µg/L total)	Freshwater sediment (mg/kg ww)	Marine sediment (mg/kg ww)	Agricultural soil (mg/kg ww)
t-OP	0.007965	6.86×10^{-4}	0.001040	7.64×10^{-5}	4.40×10^{-4}
ZnO	3.95×10^{-4}	3.69×10^{-4}	0.00463	5.75×10^{-4}	0.00192
BTA	0.02435	0.00235	0.00059	5.64×10^{-5}	2.04×10^{-4}
DBP	0.00076	6.89×10^{-5}	2.16×10^{-5}	1.31×10^{-6}	2.98×10^{-6}
Aniline	0.0870	0.00786	0.00083	6.36×10^{-5}	4.49×10^{-6}
6PPD	0.0828	7.8×10^{-4}	0.00852	0.00068	0.01289
DPG	0.00873	7.9×10^{-4}	2.6×10^{-4}	1.71×10^{-5}	3.62×10^{-6}
DCBS	0.0068	0.0006	0.0135	0.0013	0.0122
TPP	0.04438	0.00428	4.80E-03	3.92×10^{-4}	4.62×10^{-4}
CBS	0.0300	0.0029	0.0027	1.85×10^{-4}	0.0022
BENPAT	0.119	0.011	0.218	0.021	0.003
MBT	0.0483	0.0047	0.0011	9.40×10^{-5}	4.11×10^{-4}
MBTS	0.0294	0.0028	0.0060	0.0051	0.0017
IPPD	0.2327	0.0224	0.0077	6.24×10^{-4}	0.0024
44PD	0.1967	0.0019	0.00348	0.00029	0.00149
TBBS	0.0447	0.0043	7.6×10^{-4}	6.0×10^{-5}	2.9×10^{-4}
7PPD	0.1391	0.0135	0.0648	0.0059	0.0574
DPPD	0.1607	0.0154	0.3209	0.0315	0.0593
6PPD-Q	0.2813	0.0272	0.0243	0.0020	0.0085
IPPD-Q	0.2861	0.0277	0.0155	0.0013	0.0050